L Number	Hits	Search Text	DB	Time stamp
-	557	seismic and shear adj wave and velocity	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/07/22 07:54
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-	242	blanch.in.	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/23 09:22
-	2	blanch.in. and joakim	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/23 09:22
-	18	varsamis.in.	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/23 09:45
-	9	varsamis.in. and georgios	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/23 09:55
-	98	acoustic and anisotropic$3 and shear near wave and polarization$3	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/23 15:39
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-	5	5808963.uref.	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/23 16:44
-	2	4817061.pn.	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/23 16:57
-	2	5712829.pn.	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/23 16:57
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-	13	5214613.uref.	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/24 16:56
-	3	(dipole and shear and anisotropy and logging).ti.	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/27 10:15
-	32	dipole and shear and anisotropy and logging	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/01/27 10:15
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-	88	(acoustic adj waves and borehole) and polarization$4	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/07/21 16:29
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-	2	4516228.pn.	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/07/22 08:37
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-	96	(acoustic or sonic near logging$4) and (shear adj waves) and wavelet	USPAT; US-PGPUB; EPO; JPO; DERWENT; IBM_TDB	2003/07/22 10:51

Borehole Geophysics 1: W ll Logging

Tuesday Morning, October 10th

Decomposition and particle motion of acoustic dipole log in anisotropic formation BG1.1

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Abstract

For linear wave propagation in anisotropic media, the principle of superposition is still hold. The decomposition of acoustic dipole log is based on this principle. In the forward decomposition inline and crossline acoustic dipole logs at any azimuthal angle is the projection of measurements along the principle direction of the formation. In the inverse decomposition the measurements along the principle direction can be constructed from the orthogonal pair of inline and crossline acoustic dipole log. The analytic formulas for both forward and inverse decomposition of dipole log are derived in this paper. The inverse decomposition formula is the solution in the least-square sense. Numerical examples are demonstrated for acoustic dipole log decomposition in isotropic and anisotropic formations. The synthetic dipole log is calculated by 3D finite difference method. The numerical examples are also shown that the inverse decomposition formula works very well with noisy data. This inverse decomposition formula will very useful to process the field acoustic logging data in anisotropic formation. It can provide the direction of the formation anisotropy as well as the degree of anisotropy. Because acoustic dipole logging is in the near field distance, the particle motion is very complicated. Only in the principle direction the particle motion is linear polarized. The initial particle motion with dipole source at arbitrary azimuthal angle tends to point in the fast shear wave direction. But it will be difficult to use this information to find stable estimation of fast shear wave direction.

Introduction

The crust of the Earth is slightly anisotropic, which is related to geological processes. For example, anisotropy can be caused by aligned fractures in the rock. Fine layered sedimentary rocks also possess transverse isotropy. Acoustic logging provides a technique to measure formation anisotropy from drilled well.

To understand the effects of anisotropy on the fluid-filled borehole wave propagation are critical to process acoustic logging data in anisotropic formation. Several numerical techniques have been developed to simulate acoustic logging, such as discrete wavenumber method (White and Tongtaow, 1981; Chan and Tsang, 1983; Schmitt, 1989), perturbation method (Ellefsen, 1990; Sinha et al., 1994) and finite difference method (Leslie and Randall, 1992; Cheng, et al., 1995). For transversely isotropic formation with the symmetry axis aligned with the borehole axis, the solution is well known and the different type of waves are well understood. But when the symmetry axis of the TI formation makes an arbitrary angle with the borehole axis, the borehole wave propagation problem becomes much more complicated. Most of our knowledge are come from the perturbation solution. On the other hand field data observations in the anisotropic formation are available, such as borehole waves generated from vertical seismic profile (Barton and Zoback, 1988; Leveille and Seriff, 1989) and borehole dipole logging (Esmersoy, et al., 1994).

The purpose of this paper is try to answer the following three questions. How to construct the inline and crossline dipole log at any azimuthal angle from the measurement along the principle axis? What the particle motion of dipole log looks like in an anisotropic formation? How to recover the measurements along the principle axis from the inline and crossline logs at arbitrary azimuthal angle. The first and the third question are the forward and the inverse problem pair. In order to do numerical experiments the 3-D time domain finite difference method is used to generate synthetic dipole log. The formation is assumed transversely isotropic with its symmetry axis perpendicular to the borehole axis.

Forward Decomposition of Dipole Log

Although we consider wave propagation in anisotropic media, the wave motion is still governed by linear differential equations. The principle of superposition is valid. We assume that the X and the Y axis are aligned with two principle axes of anisotropy. The dipole source is in the X-Y plane and G_{ij} is the Green's function (index i and j represent x,y). The general form of dipole measurement is $R_i = G_{ij} * S_j$, where R represent receiver and S represents source. The symmetry of the model requires $G_{xy} = G_{yx} = 0$. We define that $v_x = G_{xx} * S$ is the inline dipole measurement in the X direction and $v_y = G_{yy} * S$ the inline dipole measurement in the Y direction. These measurements can be computed by finite difference method. The same dipole source with azimuthal angle θ (counterclockwise from the X axis), can be decomposed into the X and the Y directions. Then the measurement along the X axis will be:

$$v_x^\theta = v_x \cos\theta \tag{1}$$

and the measurement along the Y axis will be:

$$v_y^\theta = v_y \sin\theta \tag{2}$$

In order to demonstrate we use 3D finite difference method to compute synthetic dipole log in isotropic as well as anisotropic formations. It is a fourth-order scheme and implemented on a massively parallel computer. A more detailed descriptions of the method can be found in the paper by Cheng et al., (1995). We first consider isotropic formation. It is a slow formation with P wave velocity 2770 m/s, S wave velocity 1219 m/s. The water filled borehole is 10 cm in radius. The source is Kelly wavelet at center frequency 2 kHz. The source and the receiver are located at the center of the borehole. The source and receiver separation is 2 meters. These parameters are kept the same in the paper. The comparison of the direct finite difference computation with the projection of Equation (1) is plotted in Figure 1. The dipole source is at azimuthal angle of 45 degree. The projected and the computed waveforms are in excellent agreement.

Two types of the TI formation are considered: (1) Bakken shale, a fast formation (2) Austin chalk, a slow formation. The symmetry axis of the TI formation is perpendicular to the borehole axis. The elastic constants of these formations is give by Sinha et al. (1994). For the dipole source at azimuthal angel of 45 degree, the comparisons of direct computed waveforms with the projected one are plotted in Figure 1 for the measurement in the X direction. The formation used is Bakken shale. Once again they are in excellent agreement. Equation (1) and (2) allow you decompose the dipole

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source into the principle directions and only compute the response at the principle directions. It can save computing time for acoustic dipole log simulation in an anisotropic formation with different azimuthal directions.

From two inline dipole measurements along the X and the Y axis, the inline and crossline dipole measurements at azimuthal angle θ can be easy obtained from the projection. We have:

$$v^{\theta}_{inline} = v^{\theta}_{x} \cos\theta + v^{\theta}_{y} \sin\theta \quad (3)$$

and

$$v^{\theta}_{crossline} = -v^{\theta}_{x} \sin\theta + v^{\theta}_{y} \cos\theta \quad (4)$$

substitute Equation (1) and (2) into the above equations we obtain

$$v^{\theta}_{inline} = v_x \cos^2\theta + v_y \sin^2\theta \quad (5)$$

and

$$v^{\theta}_{crossline} = (-v_x + v_y) \sin\theta \cos\theta \quad (6)$$

the same equations are also given by Sinha et al. (1994) and Esmersoy et al. (1994). These are our forward decomposition formulas for acoustic dipole log. To show some examples, we projected the inline and the crossline dipole log in Austin chalk formation at different azimuthal angles. The waveforms are plotted in Figure 2 In isotropic formation the crossline dipole log is zero. In anisotropic formation the crossline dipole vanishes only when the dipole source is aligned with the symmetry axis. The crossline dipole log generally is not zero. In logging data processing the crossline dipole log can be used to determine whether the formation shear wave velocity is anisotropic and the direction of principle axis of the anisotropy. In inline dipole log (Figure 2) it is clear from the waveforms that at 90 degree azimuthal angle the arrival times are earlier than at 0 degree. This is the reflection of the shear wave velocity azimuthal dependent. The inline dipole log can provide the measurements of anisotropy from the arrival time differences between different azimuthal angles.

Particle Motion and Polarization Analysis

The shear wave splitting is often observed from the teleseismic events. The particle motion of shear wave is polarized along the principle directions. If acoustic dipole log in anisotropic formation is also polarized along the principle directions, then we can find the principle direction from polarization analysis. This will make it very easy to solve the inverse decomposition question.

We define the mean value of N observations of variable $x(i)$ as (Kanasewich, 1981)

$$E(x) = \frac{1}{N} \sum_{i=1}^{N} x(i) \quad (7)$$

and covariance between two variables x_1 and x_2 as

$$Cov[x_1, x_2] = \frac{1}{N} \sum_{i=1}^{N} (x_1(i) - E(x_1))((x_2(i) - E(x_2)) \quad (8)$$

For the two components of dipole log (v_x, v_y), the covariance matrix **C** can be formed as

$$\mathbf{C} = \begin{pmatrix} Cov[v_x, v_x] & Cov[v_x, v_y] \\ Cov[v_y, v_x] & Cov[v_y, v_y] \end{pmatrix} \quad (9)$$

If λ_1 and λ_2 are the eigenvalues of the covariance matrix **C** and $\lambda_1 \geq \lambda_2$, then the quantity

$$P = 1 - \frac{\lambda_2}{\lambda_1} \quad (10)$$

estimate the rectilinearity of the particle motion. When the rectilinearity is high ($\lambda_1 \gg \lambda_2$) the particle motion is close to linear polarization. When the rectilinearity is near zero ($\lambda_1 \simeq \lambda_2$) the particle motion is near circular. The direction of polarization may be measured by considering the eigenvector associated with the largest eigenvalue.

In TI formations shear wave velocity is azimuthal dependent. The particle motions are plotted in Figure 3 for Austin chalk. From the particle motion plots, the linear polarizations at azimuthal angles of 0 and 90 degree are easy to understand. The symmetry of the model requires that there is no motion perpendicular to the plane of the symmetry ($G_{xy} = G_{yx} = 0$). The linear polarized particle motions at azimuthal angles of 0 and 90 degree also give some indirect accuracy measure of finite difference method. When the dipole source is not aligned with the principle axis of the formation we would intuitively expect that it will polarized along the two principle axes. But the plot of the particle motion did not show these polarizations clearly. The reason is that our intuition are based on the far-field shear body waves in anisotropic media. The dipole log is using flexural wave which is a guided mode and the acoustic logging distance is belong to the near field. In general for one period of separation in time domain takes the distance about wavelength divided by the percent of anisotropy. For example a 5% anisotropy takes about 20 wavelengthes to get one period separation in time.

In order to verify the distance effect we increase the source and receiver distance to 4.5 meters in Austin chalk formation to do the finite difference calculations. Other parameters are not changed. The particle motion is plotted in Figure 4. It is very clear from the plot that the particle motion is started in the fast shear wave direction. This example supports that no clear polarized particle motion in dipole log is due to the nature of near-field logging.

The rectilinearity analysis of the dipole particle motion in Bakken shale and Austin chalk are listed in Table 1. At azimuthal angle of 0 and 90 degree the particle motion is linear polarized. The particle motion with source at arbitrary azimuthal angle did not show any particular patterns. The particle motion pattern is depend on the relative phase of the Green's function G_{xx} and G_{yy}. This phase is depend on the source receiver distance, degree of anisotropy and frequency. From the particle motion analysis we only see the initial particle motion is directed along the fast shear wave direction with large source receiver separation. But due to the near field nature of acoustic logging this initial particle motion is hard to obtain accurately for any practicle use. In order to answer the final question we have to seek another way to do the inverse decomposition.

Inverse Decomposition of Dipole Log

In the field logging situations, we don't know the principle direction of the formation. The inverse problem is how to find the principle direction from the measurement at arbitrary azimuthal angle. We assume two pair of inline and crossline dipole measurements are collected in perpendicular directions. The measured data is represented as a data vector $\mathbf{V} = (v(t_1), v(t_2), ..., v(t_n))^T$. The two inline dipole measurements are $\mathbf{V}^{\theta}_{il}$ and $\mathbf{V}^{\theta+90}_{il}$. The two crossline dipole measurements are $\mathbf{V}^{\theta}_{cl}$ and $\mathbf{V}^{\theta+90}_{cl}$. The problem becomes how to find azimuthal angle θ and inline measurements along the X and the Y axis from these four data vectors. By using Equation (5) and (6) we have:

V · c \ Sx
N b - Vd \ Sy

$$V_{il}^{\theta} = V_x \cos^2\theta + V_y \sin^2\theta \quad (11)$$
$$V_{il}^{\theta+90} = V_x \sin^2\theta + V_y \cos^2\theta \quad (12)$$
$$V_{cl}^{\theta} = (-V_x + V_y)\sin\theta\cos\theta \quad (13)$$
$$V_{cl}^{\theta+90} = (V_x - V_y)\sin\theta\cos\theta \quad (14)$$

Equation (14) is not independent one because $V_{cl}^{\theta} = -V_{cl}^{\theta+90}$. So it left us with three equations with three unknowns. The three unknowns are angle θ, V_x and V_y. With a few algebra manipulations of Equation (11), (12) and (13) we obtain:

$$V_{cl}^{\theta}(\tan\theta - \cot\theta) = V_{il}^{\theta} - V_{il}^{\theta+90} \quad (15)$$
$$V_x = V_{il}^{\theta} - V_{cl}^{\theta}\tan\theta \quad (16)$$
$$V_y = V_{il}^{\theta+90} + V_{cl}^{\theta}\tan\theta \quad (17)$$

notice that Equation (15) containes n equations, where n is the number of measurements. So angle θ is overdetermined. We seek the least-square solution for θ. This solution is given below:

$$\tan^2\theta - \frac{(V_{cl}^{\theta})^T \cdot (V_{il}^{\theta} - V_{il}^{\theta+90})}{(V_{cl}^{\theta})^T \cdot V_{cl}^{\theta}}\tan\theta - 1 = 0 \quad (18)$$

θ can be easy to obtain by finding the root of second-order polynomial. Once θ is known, V_x and V_y can be calculated directly from Equation (16) and (17). So inverse decomposition is given by the analytical expressions in the least-square sense.

Next we consider a numerical example. Austin chalk formation is considered once again. First we determine the rotated angle θ by using Equation (18). The inline and crossline dipole logs are obtained by using Equation (5) and (6). And these data are used to recover the rotated angle. Random noise is added into the inline and the crossline data to test sensitivity of the formula to noise. The recovered angles are listed in Table 2. If there is no noise added into the data the rotated angles are recovered almost exactly. With 5% noise the differences between recovered angle and actual rotated angle are less than 0.5 degree. When noise level increased to 10% the differences are less than 1.5 degree. Under the noise condition the inverse decomposition formula still can give very good estimation of the principle direction. Recovered waveforms along the principle direction are plotted in Figure 5. The inline and crossline logging data at azimuthal angles of 30 and 120 degree are used. The inline and crossline waveform at azimuthal angle 30 can be found in Figure 2. The four traces shown in the plots are original data, recovered from noise free, 5% noise and 10% noise data. The waveforms along the principle directions are recovered very well even under noisy condition. The inverse decomposition formulas are very computational efficient. It can be used to process field acoustic logging data in anisotropic formation.

Conclusions

In this paper the analytic expressions are obtained for both forward and inverse decomposition of acoustic dipole logging data. These decomposition formulas are valid because the principle of superposition is hold for linear wave propagation in anisotropic media. These very simple analytic formulas can be directly applied to field logging data processing. The synthetic acoustic dipole logs are used to demonstrate these forward and inverse decompositions. The synthetics are calculated by 3-D finite difference method. The numerical examples are shown that inverse decomposition formula works very well with noisy data. The particle motion of dipole log in anisotropic formation is very complicated. This is because the acoustic logging distance is in the near field. The particle motion with dipole source aligned with principle direction is linear polarized. When the dipole source is at arbitrary azimuthal angle the initial particle motion tend to point to the fast shear wave direction. But this initial polarization can only have very limited use in the field data situation.

Acknowledgments

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Source direction	Rectilinearity		
(degree)	shale (2m)	chalk (2m)	chalk (4.5m)
0	1.00	1.00	1.00
15	0.98	0.97	0.95
30	0.95	0.93	0.83
45	0.96	0.93	0.75
60	0.98	0.96	0.84
75	0.99	0.99	0.95
90	1.00	1.00	1.00

Table 1: Polarization analysis of dipole log. The formations are Bakken shale and Austin chalk. The source-receiver separations are 2 and 4.5 meters.

Rotation angle (degree)	Recovered angle noise (0%)	noise (5%)	noise (10%)
5	5.00	5.17	5.51
15	15.00	15.43	16.26
30	30.00	30.44	31.22
45	45.00	45.09	45.15
60	60.00	59.82	59.24
75	75.00	74.82	74.19

Table 2: Recovered rotation angle from inline and crossline data. Random noise are added into the data.

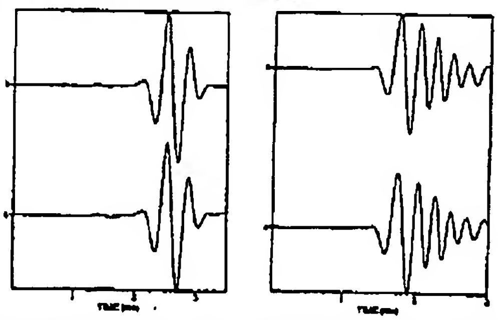

Figure 1: Comparison of the finite difference synthetic with linear decomposition. Dipole source is at azimuthal angle of 45 degree. The waveform in the X direction is shown. Trace (a) finite difference synthetic. Trace (b) decomposition according to Equation (1). On left isotropic formation. On right anisotropic formation.

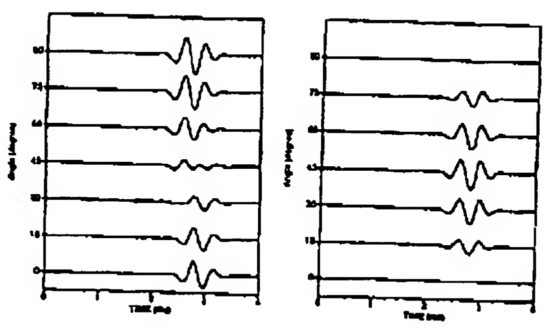

Figure 2: Projected dipole log in Austin chalk formation at different azimuthal angles by using Equation (5). On left inline dipole. On right crossline dipole.

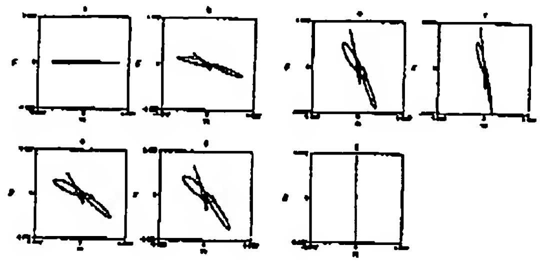

Figure 3: X-Y plane particle motion of dipole log in Austin chalk formation. The azimuthal angle of the dipole source is (a) 0. (b) 15. (c) 30. (d) 45. (e) 60. (f) 75. (g) 90.

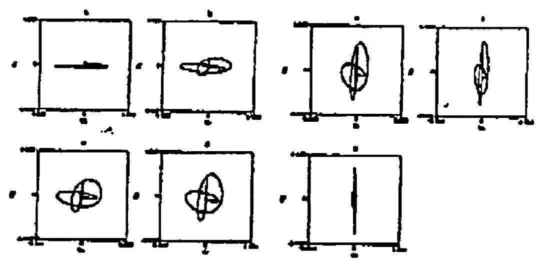

Figure 4: X-Y plane particle motion of dipole log in Austin chalk formation. The source-receiver distance is 4.5 meters. The azimuthal angle of the dipole source is (a) 0. (b) 15. (c) 30. (d) 45. (e) 60. (f) 75. (g) 90.

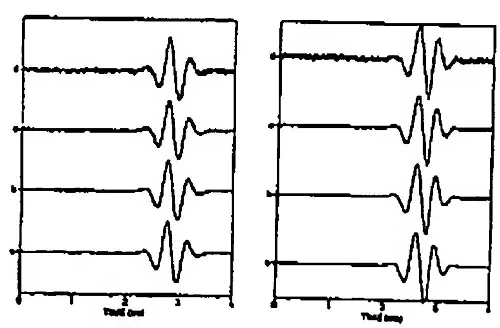

Figure 5: Recovered waveforms from 30 and 120 degree inline and crossline dipole logs. The formation is Austin chalk. Trace (a) original waveform along the X axis. Trace (b) recovered from data without noise. Trace (c) recovered from data with 5% random noise. Trace (d) recovered from data with 10% random noise. On left the X direction. On right the Y direction.

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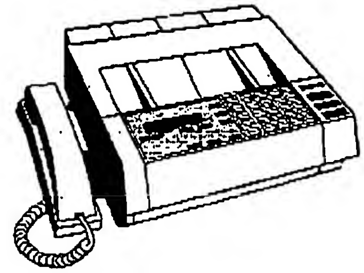

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